TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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THE EFFECT OF SLOTS AND FLAPS ON LATERAL CONTROL OF

A LOW-WING MONOPLANE AS DETERMINED IN FLIGHT

By Hartley A. Soulé and J. W. Wetmore
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SUMMARY

This paper presents the results of flight tests made
to determine the effect of slots and flaps on the lateral
control of a low-wing monoplane. Maximum angular acceler-
ations in roll and yaw produced by sudden application of
the ailerons and maximum accelerations in yaw produced by
sudden application of the rudder during gliding flight were
recorded for the following wing arrangements: (a) no aux-
iliary device; (b) full-span slots; (c) plain flaps;
(d) flaps and full-span slots; (e) wing-tip slots. Roll-
ing- and yawing-moment coefficients were derived from the
accelerations.

The full-span slots and the flaps each had about the
same influence on the aileron rolling moments. At values
of the lift coefficient obtainable with the plain wing,
the effect of these devices was negligible. At the higher
lift coefficients obtainable with these devices, the roll-
ing-moment coefficients increased slightly but, despite
this increase, the aileron effectiveness progressively de-
creased with increasing lift coefficient, owing to the
corresponding reduction in air speed. In the range cov-
ered by the tests, the effectiveness of the controls was
appreciably reduced by the wing-tip slots. The adverse
yawing moment of the ailerons experienced at the large
lift coefficients obtained with the flaps was appreciably
less than at similar lift coefficients obtained with ei-
ther full-span or wing-tip slots. The yawing moments pro-
duced by the rudder were only slightly affected by the use
of the auxiliary devices. The airplane was found to be
laterally unstable with all combinations tested. Because
of the angular velocities acquired in the time taken to
deflect the ailerons the rolling moments recorded in flight
were only about two thirds the values that would have been
obtained with the wing restrained as in wind-tunnel tests.

INTRODUCTION

In connection with a general study of means of decreasing the landing and take-off speeds of airplanes, and of providing control and stability at these speeds, an investigation of the general flight characteristics of an airplane equipped with slots and flaps was undertaken. Two arrangements of the slots were investigated; namely, full-span slots, which have the primary function of increasing the maximum lift coefficient and consequently decreasing the landing and take-off speeds; and wing-tip slots, which principally affect the lateral stability at low speeds and have only a small influence on the maximum lift coefficient. The effect of the full-span slots and the flaps on the lift and drag characteristics of the McDonnell airplane which was used in this investigation has been previously reported in reference 1. The present paper deals with the effect of these devices as well as wing-tip slots on the lateral control and, to some extent, on the lateral stability of the airplane.

The flight tests were made to determine the lateral-control characteristics for the following wing conditions:

    (a) No auxiliary device

    (b) Full-span slots

    (c) Flaps

    (d) Full-span slots and flaps

    (e) Wing-tip slots

The tests were made in the range of angles of attack above 12°, since the slots and flaps would not ordinarily be utilized at smaller values of the angle of attack. The extended low-speed range made available by the slots and flaps was covered so that results for these conditions could be compared with those obtained at angles of attack below the stall of the plain wing. As the wing-tip slots are known to have their greatest effect on the lateral stability at angles of attack beyond the stall (reference 2), it was originally intended that the flight tests should include the stalled-flight range. Unfortunately, this phase of the work was prevented by violent tail buffeting at the stall.

The control tests consisted of a determination of the
maximum angular accelerations in roll and yaw following an
abrupt full displacement of the ailerons or the rudder
during a steady glide. From these accelerations, rolling
and yawing moments were derived and the rolling criterion
RC obtained. In the stability tests, records of the an-
gular motion of the airplane following representative con-
trol movements were obtained. The latter tests were per-
formed at only two angles of attack, 12° and an angle just
below the stall for each condition.

APPARATUS AND METHOD

Airplane.- The McDonnell airplane used in these tests
is a low-wing monoplane equipped with full-span automatic
leading-edge slots and with trailing-edge flaps extending
from the fuselage to the ailerons. The slots are construct-
ed in four sections so that it is possible to operate them
either as full-span slots or, by locking the inboard por-
tions, as wing-tip slots. A front-view photograph of the
airplane with the flaps depressed is shown in figure 1.
Figure 2 shows the wing layout. The principal character-
istics of the airplane are given in table I. The relative
motions of the differential ailerons are shown in figure 3.

The lift and drag characteristics of the airplane
for the wing conditions investigated in these tests are
given in figure 4. This figure is a reproduction of fig-
ure 14 in reference 1, with lift and drag characteristics
for wing-tip slots, determined in a comparable manner,
added.

Instruments.- Three angular-velocity recorders, an
air-speed recorder, a control-position recorder, and a
timer were installed in the airplane during the tests.
The angular-velocity recorders were used to measure the
rate of rotation about the three body axes of the airplane.
Soon after the start of the tests, it was found from lab-
oratory experiments that considerable difficulty from lag
might be experienced for the accelerated-flight conditions
unless special precautions were observed. As the instru-
ments are oil-damped, the lag characteristics vary with
temperature. In order to insure a constant oil viscosity
of proper magnitude, the instruments were enclosed in an
insulated box in which a constant temperature was main-
tained for all flight tests. The proper corrections for

lag at the temperature at which the instruments were main-
tained were determined from the results of the laboratory
experiments.

The air-speed recorder was used only for the purpose
of determining air speed at the start of a maneuver. The
recorder was connected to a swiveling pitot-static head
mounted about one chord length ahead of the wing, the cor-
rection for this position having been previously obtained
in a calibration against a trailing air-speed head during
steady glides. The control-position recorder was utilized
to obtain continuous records of the movement of the aile-
rons and rudder. The timer was used for the synchroniza-
tion of records obtained with the above-mentioned instru-
ments, and to provide a time scale on these records.

Tests.- The aileron-control tests consisted of record-
ing the velocity of the airplane in rolling and yawing im-
mediately following an abrupt full displacement of the
stick to the right during a steady glide, the other con-
trols being held neutral. The tests for each wing arrange-
ment were repeated at several air speeds, varying from that
corresponding to an angle of attack of $12°$ to the minimum
speed attainable without serious tail buffeting. The rec-
ords thus obtained were differentiated graphically to de-
termine the maximum angular accelerations in roll and yaw.
Corrections were applied for lag as previously mentioned.
Rolling- and yawing-moment coefficients were derived from
the angular accelerations by means of the following equa-
tions:

$$C_l = \frac{\frac{dp}{dt} A}{q \, b \, S}$$

$$C_n = \frac{\frac{dr}{dt} C}{q \, b \, S}$$

where A and C are the moments of inertia about the X
and Z body axes, respectively, q refers to the initial
air speed, and the other symbols have their usual signifi-
cance.

The rudder-control tests were carried out in a manner
similar to that employed for the aileron-control tests,
with the exception that only the acceleration in yawing
was considered.

Records of the angular velocities about the three body axes were made with each wing arrangement for the following control movements, to determine qualitatively the effectiveness of the lateral controls when used after motion had started and to obtain an indication of the lateral-stability characteristics of the airplane:

(a) Stick hard right - stick centralized, rudder neutral throughout.

(b) Stick hard right - stick hard left, rudder neutral throughout.

(c) Rudder hard right - rudder centralized, stick neutral throughout.

(d) Rudder hard right - rudder hard left, stick neutral throughout.

(e) Rudder hard right - rudder centralized, stick hard left.

The second displacement in each case was made approximately 2 seconds after the initial displacement. These tests were made at two angles of attack for each wing arrangement, 12° and an angle of attack just below the stall. Time histories of angular velocities were plotted from the records obtained.

RESULTS

The results of the tests are shown in graphical form in figures 5 to 15. Figure 5 shows the maximum rolling and yawing accelerations resulting from abrupt movements of the ailerons. The corresponding rolling- and yawing-moment coefficients are plotted in figure 6. Figures 7 and 8 present similar information concerning the yawing moment produced by the rudder. A comparison of the yawing moments produced by the ailerons and rudder is given in figure 9. Figures 10 to 14 show, for representative cases, time histories of angular velocities obtained for the various control movements utilized in the tests made to determine the effectiveness of the controls when used after motion had started. The rolling criterion RC is given in figure 15.

DISCUSSION

A comparison of the coefficients of rolling and yawing moment for the airplane can be obtained by reference to figure 6. In this figure it will be seen that for the plain wing the rolling-moment coefficient increases slightly with lift coefficient until a critical lift coefficient is reached, above which the rolling-moment coefficient decreases rapidly. Inspection of figure 4 shows that the critical lift coefficient corresponds approximately to the start of the burble, as indicated by the rapidly decreasing slope of the lift curve at this point. The trend of the curves of rolling-moment coefficient appears to be similar for the other wing conditions, the only possible exception being that of the combination of flaps and full-span slots. For this case the tests could not be carried up to the critical lift coefficient, owing to tail buffeting. From the fact that the curves for the conditions where the flaps and the full-span slots were used separately appear as extensions of the curve for the plain wing, it is concluded that an envelope curve for these three conditions may be taken as representative of the aileron moment for unburbled flow over the wing, and that the shape of this curve is independent of means taken for maintaining smooth flow. Thus, the flaps and the full-span slots, in performing their basic function of maintaining smooth flow to higher lift coefficients than are possible with the plain wing, assist the ailerons in providing lateral control at the speeds and attitudes made possible through the use of these auxiliary devices. The reason for the curve for the flaps and full-span slots when used together not being a continuation of the curves for the conditions just discussed, may be that a partial breakdown of the flow occurred considerably before the wing was completely stalled - indicated in figure 4 by a deviation of the lift curve from a linear variation with angle of attack, and observed in flight by tail buffeting. With wing-tip slots the rolling moment coefficients are definitely lower than with the plain wing.

The yawing-moment coefficients produced by the ailerons are adverse for all wing conditions. The curves for each condition show the same general trend as the curves of rolling-moment coefficient, although the yawing-moment coefficients do not fall off as rapidly as do the rolling-moment coefficients when burbling starts. The curves of yawing moment when slots alone are used appear as exten-

sions of the curve of yawing moment for unburbled flow on
the plain wing. For the flaps, however, there is an ap-
preciable decrease in the yawing moment due to the ailerons.

As regards the directional control, only the yawing
moment due to the rudder has been considered, the rolling
moment being a secondary effect. For the plain wing the
yawing-moment coefficients (fig. 8) decrease a small amount
with increasing lift coefficients. The slots and flaps,
when used either separately or together, increase the yawing
moment appreciably, the increase being approximately one
third. The wing-tip slots have practically no effect on
the rudder control.

A comparison of the yawing moments produced by the
ailerons and rudder is interesting in that it indicates
whether or not the rudder is capable of overcoming the ad-
verse yaw of the ailerons. The yawing-moment coefficients
for the ailerons and rudder have been plotted in figure 9.
It will be noted that throughout the entire flight range
the rudder moment is always greater than the aileron moment
but, at the higher lift coefficients, the excess becomes
very small.

The time histories of angular velocities resulting
from various control movements indicated that for all wing
conditions within the range of angles of attack tested the
ailerons and rudder were not only effective in starting a
rolling or yawing motion in the desired direction as has
been noted, but were also capable of checking and revers-
ing angular motion present when the controls were applied.
There were, of course, differences between the various
wing conditions in the motions following the second con-
trol movement of the control-reversal tests, but these
were not of a nature to permit definite comparisons of the
control effectiveness between any one wing condition and
another, considering the differences in attitude and in
the magnitude of the angular velocities, and in other such
influencing factors at the time that the controls were re-
versed.

The airplane was found to exhibit spiral instability
for all wing conditions and for all angles of attack. At
an angle of attack of 12°, this tendency was apparently
the same for all wing conditions.

A comparison of the aileron effectiveness on the ba-
sis of the rolling-moment coefficient C_l is not entirely

satisfactory, as the actual moments that can be obtained
are dependent on air speed. For example, the aileron ef-
fectiveness, as indicated in figure 5 by the angular accel-
erations, decreased considerably with decreased air speed,
although the rolling-moment coefficient at the lowest speed
was greater than that at the highest speed. Thus it is ev-
ident that although the full-span slots and the flaps ex-
erted a favorable influence on the aileron control by main-
taining smooth flow over the wings and actually increased
the rolling-moment coefficient, the effect was not suffi-
cient to compensate for the reductions in speed obtained
with these devices. The decrease in control effective-
ness in the range of lower speeds was sufficient to cause
the lateral control, which was regarded as satisfactory
in the range of higher speeds, to become sluggish and unsat-
isfactory.

The lateral-control effectiveness can be represented
in nondimensional form by means of the rolling criterion
RC explained in reference 3, which for rectangular wings
becomes C_l/C_L. In this reference a value of 0.075 for
the criterion is assumed to be satisfactory. Inasmuch as
the transition from satisfactory to unsatisfactory aileron
control occurs within the range used in the tests, it is
interesting to compare the flight results with this assumed
satisfactory value of the criterion. Before this compari-
son can be made, however, it is necessary to consider the
different conditions under which the flight and wind-tunnel
tests are made and how these differences affect the results.
Curves of aileron deflection and rolling velocity for a typ-
ical flight test are shown in figure 16. It will be noted
that in the time required for the control to be fully de-
flected and the maximum acceleration attained, the air-
plane had acquired an appreciable rate of roll. The damp-
ing set up by this velocity reduced the aileron moment be-
low that which would be obtained were the rate of roll zero,
as is the case in wind-tunnel tests. It is also probable
that the acceleration itself has some effect on the aerody-
namic forces, the extent of which is not known. The effect
of the damping can be estimated on the basis of the assump-
tion that at the maximum angular velocity the damping mo-
ment is equal to the aileron moment for zero roll, and that
at angular velocities less than the maximum the damping is
proportional to the angular velocity. Data given in refer-
ence 4 show that these assumptions are valid, at least for
pure roll. Thus, for the case shown in figure 16, the ai-
leron rolling moment calculated from the maximum accelera-
tion is only two thirds of the moment that would be obtained

were the rate of roll zero. A similar check of the records for the remainder of the tests indicates that the rolling moments are from two thirds to three fourths of the values that would be obtained if the rate of roll were zero. It is evident that this fact must be taken into account in the comparison of rolling moments or values of RC obtained from flight and wind-tunnel tests.

Values of RC calculated from the flight tests are shown in figure 15. The values range from 0.032 where control was satisfactory, to 0.015 where control was unsatisfactory. It now seems reasonable to assume that 0.03 for the flight condition represents satisfactory control, so that this value divided by 2/3 represents satisfactory control for the wind-tunnel condition in which the rate of roll is zero. The value thus obtained is 0.045, as compared with the assumed satisfactory value of 0.075. Of course this comparison is strictly applicable only to the McDonnell airplane as the factor 2/3 is to some extent dependent on the stick force and moment of inertia of the airplane about its longitudinal axis. It seems probable, however, that the assumed satisfactory value of RC of 0.075 can be safely revised downward by an appreciable amount.

CONCLUSIONS

1. At lift coefficients less than that corresponding to maximum lift for the plain wing, flaps and full-span slots had no appreciable effect on the lateral control obtained with the ailerons, but wing-tip slots decreased the control effectiveness appreciably.

2. At lift coefficients greater than the maximum obtainable with the plain wing, the effect of flaps and full-span slots was to maintain reasonably large values of the rolling-moment coefficient over the extended range of lift coefficients obtainable with these devices.

3. Although rolling-moment coefficients tended to increase to some extent with increasing lift coefficients, there was a marked decrease in control effectiveness at the highest lift coefficients obtained owing to the reduced air speed.

4. Adverse yawing moment of the ailerons was less when the flaps were used to obtain a given lift coefficient

than when slots were used to obtain the same lift coeffi-
cient.

     5. The yawing moments produced by the rudder were
only slightly affected by the use of the auxiliary devices.

     6. The airplane was laterally unstable with the plain
wing, and no combination of slots and flaps tested improved
this condition.

     7. As a result of the angular velocity acquired in
the time taken to fully deflect the ailerons, maximum roll-
ing moments were only about two thirds as great as would
be obtained for equal deflection and zero rate of roll.

Langley Memorial Aeronautical Laboratory,
     National Advisory Committee for Aeronautics,
          Langley Field, Va., November 2, 1933.

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TABLE I

Characteristics of the McDonnell Airplane
General

Span (b)	35 ft.	Height	7 ft. 2-1/2 in.
Chord (c)	5 ft.8 in.	Weight (test)	1,852 lb.
Area	196.5 sq.ft.	Moment of inertia about	
Aspect ratio	6.2	X axis	1,345 slug ft.^{2}
Wing section	M-6	Moment of inertia about	
Dihedral	4.5°	Z axis	2,280 slug ft.^{2}
Angle of wing setting	2.3°	Distance from leading edge to c.g.	22.7 in.
Over-all length 21 ft.4 in.			33.4 percent c

Slots and Flaps

Over-all span of slat   31 ft. 7-1/2 in.
Span of a tip section of slat   5 ft.; 28.5 percent b/2
Chord of slat   10.2 in.; 15 percent c
Location of slat with slot open:
            Width .... 5.43 in.; 8 percent c
            Depth .... 2.38 in.; 3.5 percent c
            Gap .... 1.02 in.; 1.5 percent c
Span of flaps .... 22 ft. 4-1/8 in.
Chord of flaps .... 1 ft. 5-7/16 in.;
                                    25.6 percent c
Flap angle when fully depressed −40°

Lateral-Control System

Aileron span .... 4 ft. 7-15/16 in.;
                                   27.6 percent b/2
Aileron chord .... 1 ft. 5-7/16 in.;
                                   25.6 percent c
Aileron movement .. .. Differential 25° up, 10°
                                    down
Fin area .... 6 sq.ft.
Rudder area .... 7-1/2 sq.ft.
Rudder movement .... ±30°
Distance from c.g. to rudder
  post .... 14 ft.

Figure 1. - Front view of the McDonnell airplane, showing slots and flaps

Fig. 1
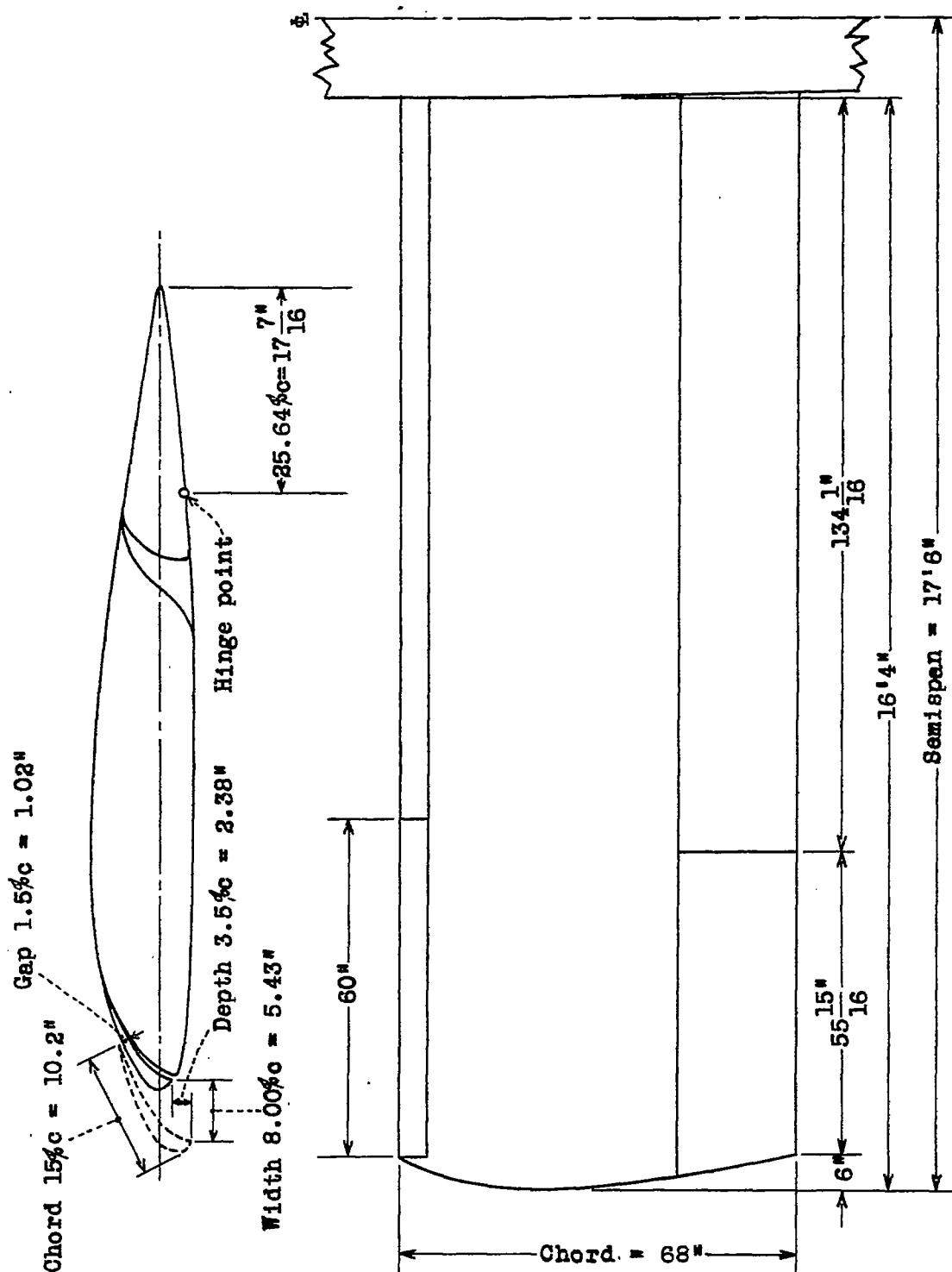
Figure 2.   Arrangement and dimensions of slots, flaps, and ailerons on the McDonnell airplane.
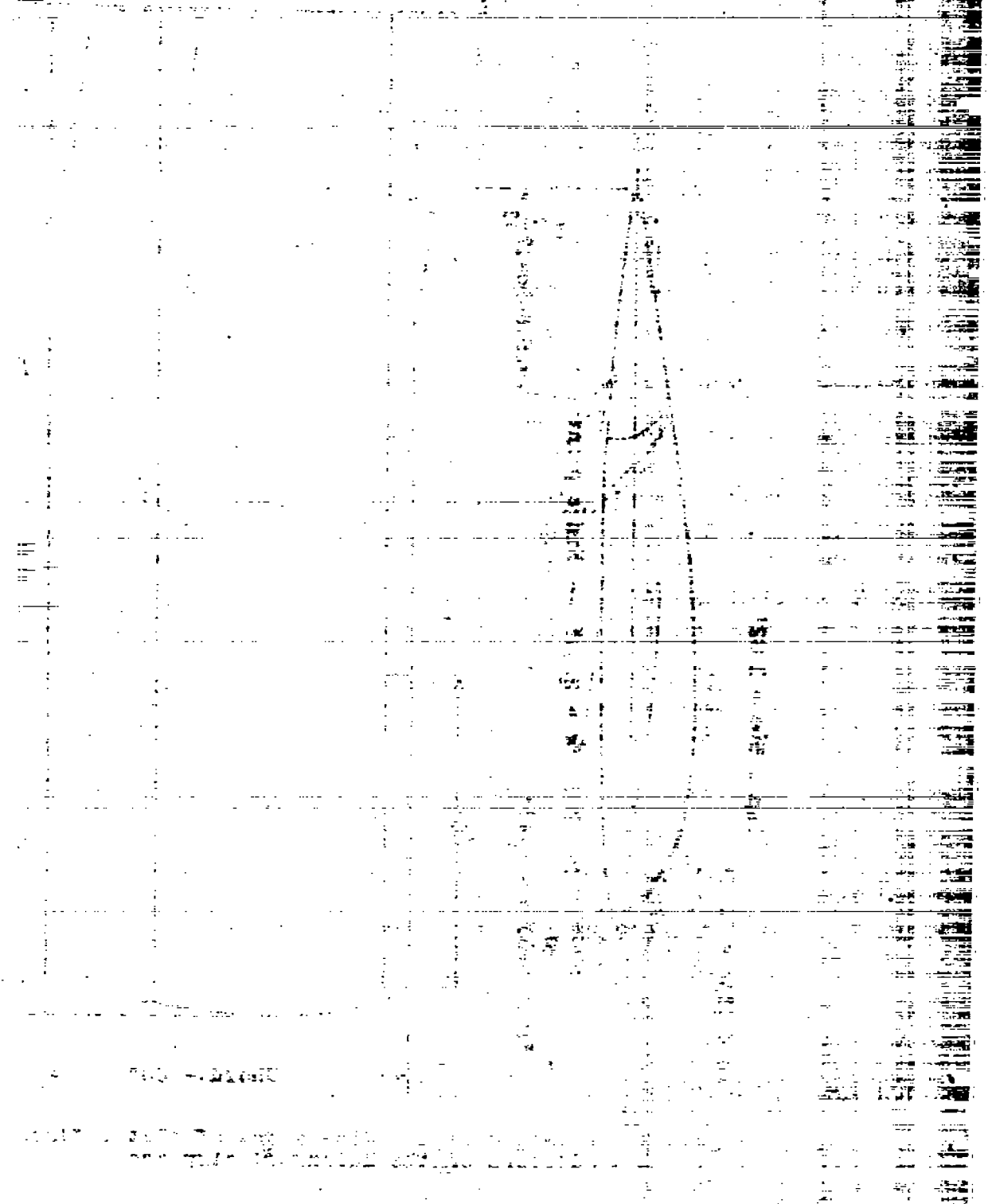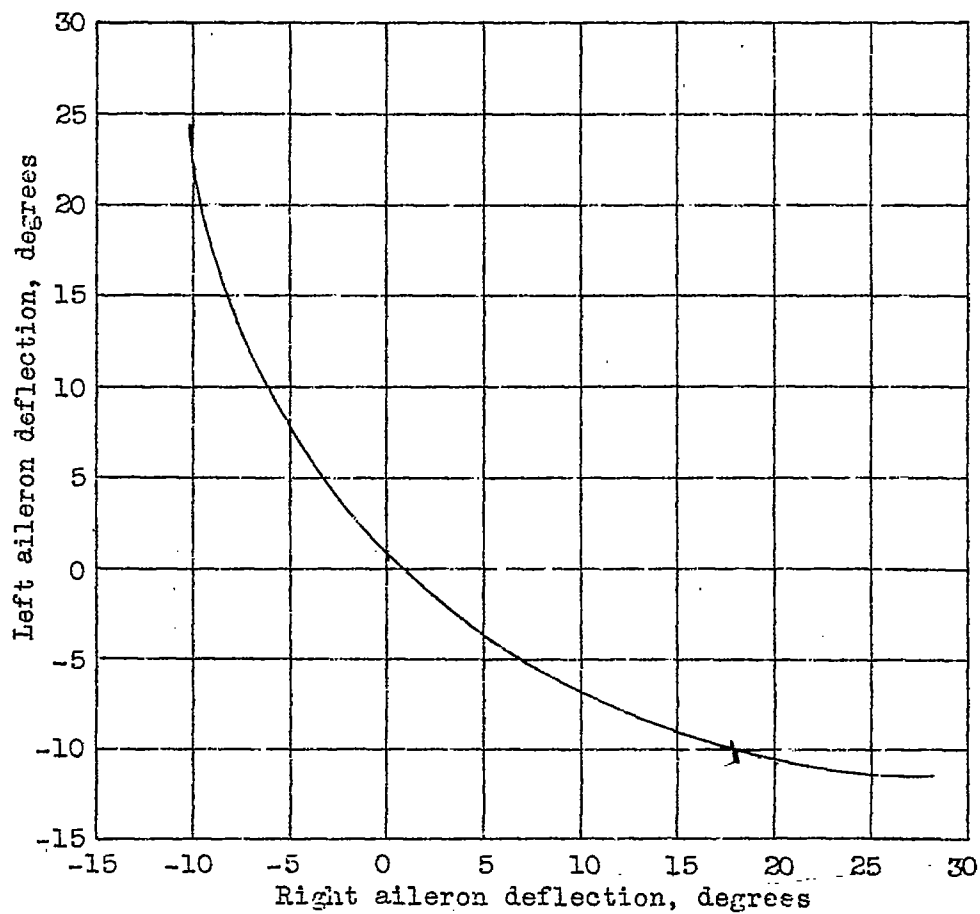
Figure 3.- Differential movement of ailerons on the McDonnell
          airplane.
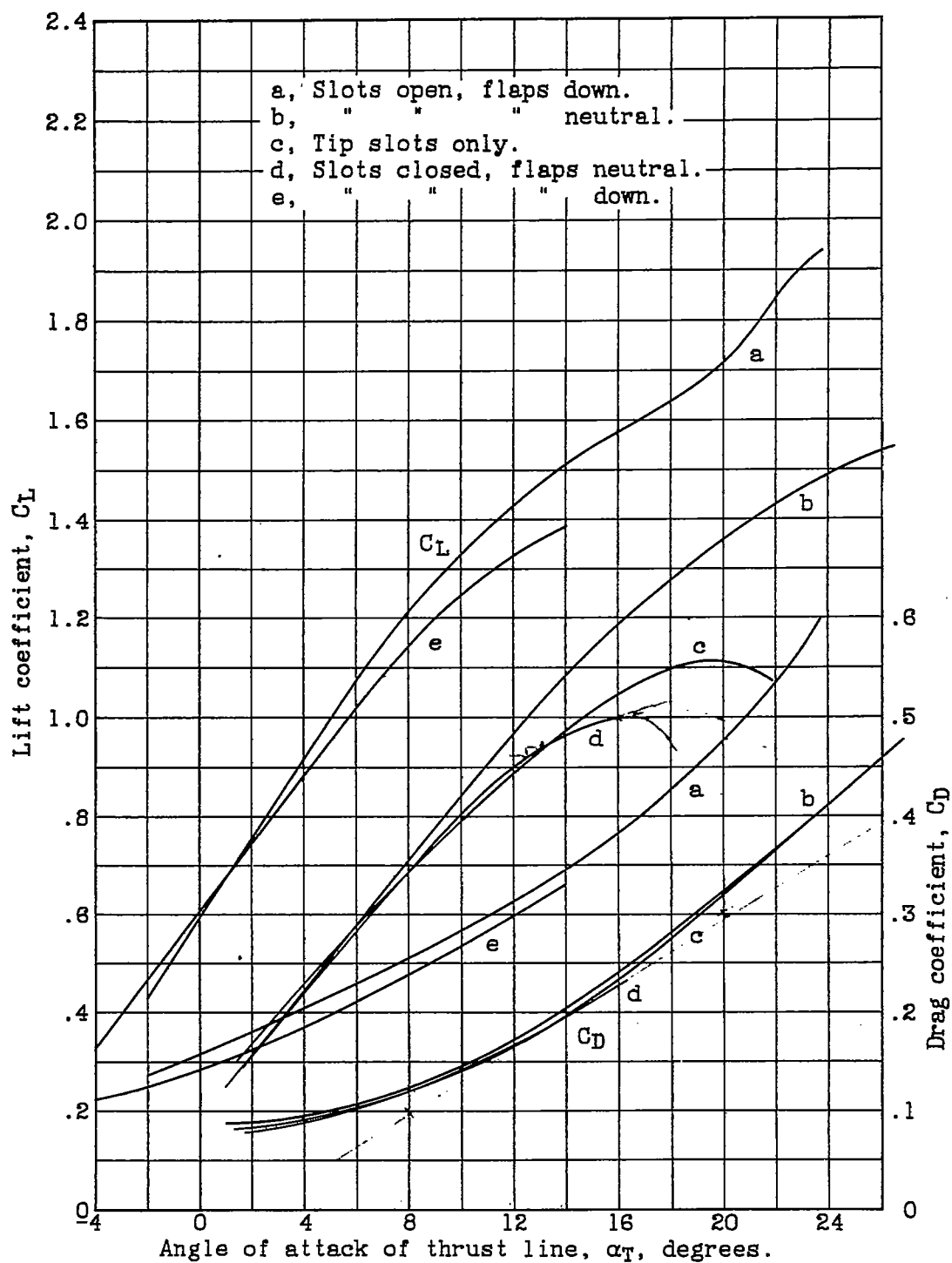
Figure 4.-Lift and drag coefficients of the McDonnell airplane with various combinations of slots and flaps.
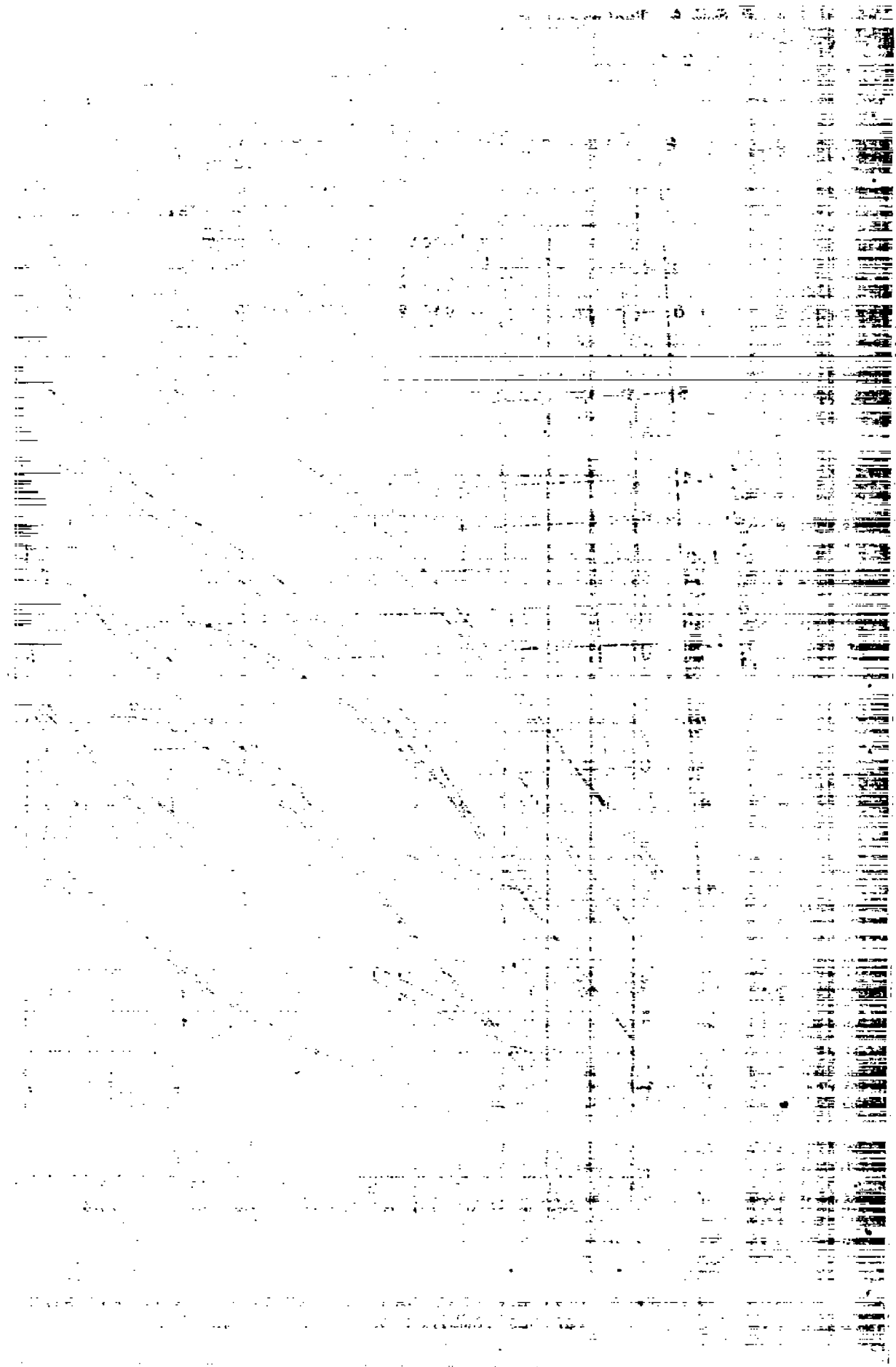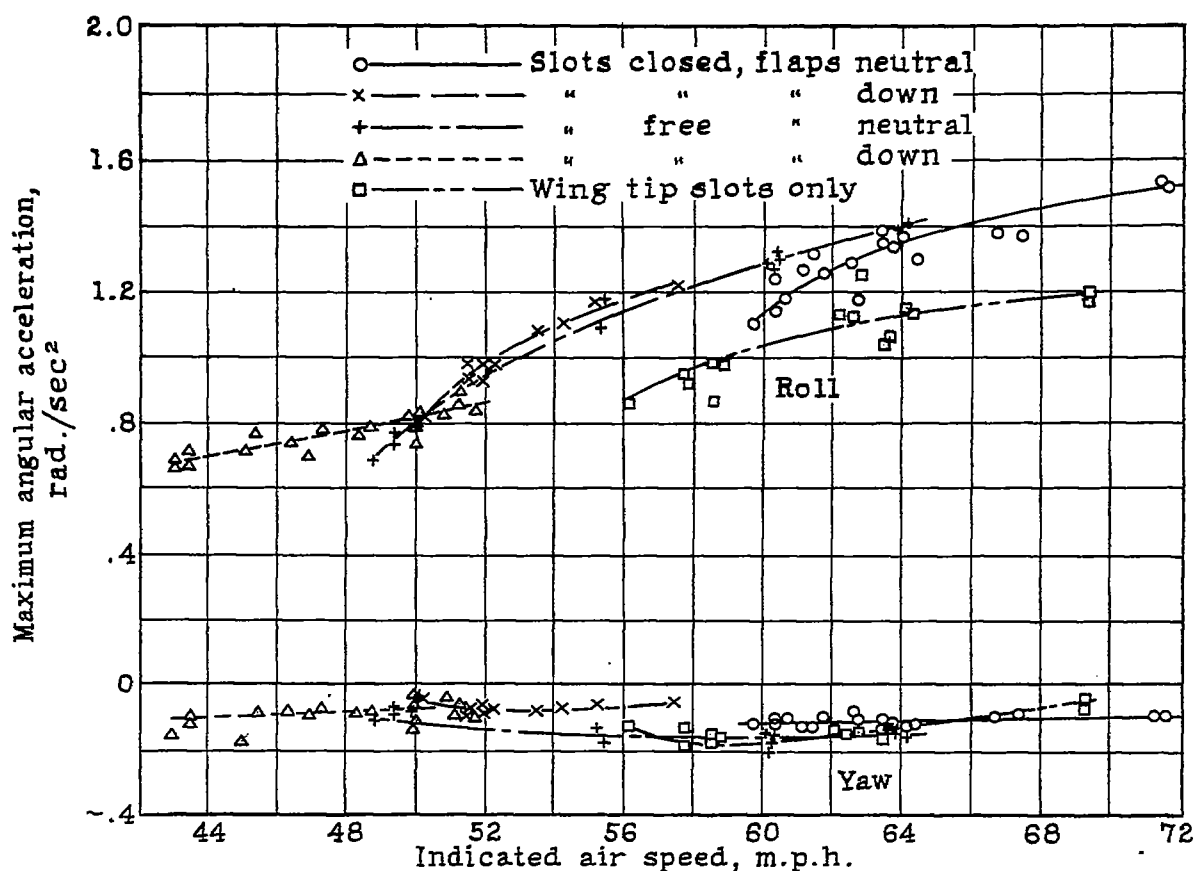
Figure 5.- Variation of maximum rolling and yawing acceleration about
        body axes, with indicated air speed, for full positive ailer-
on deflection. (All wing conditions.)
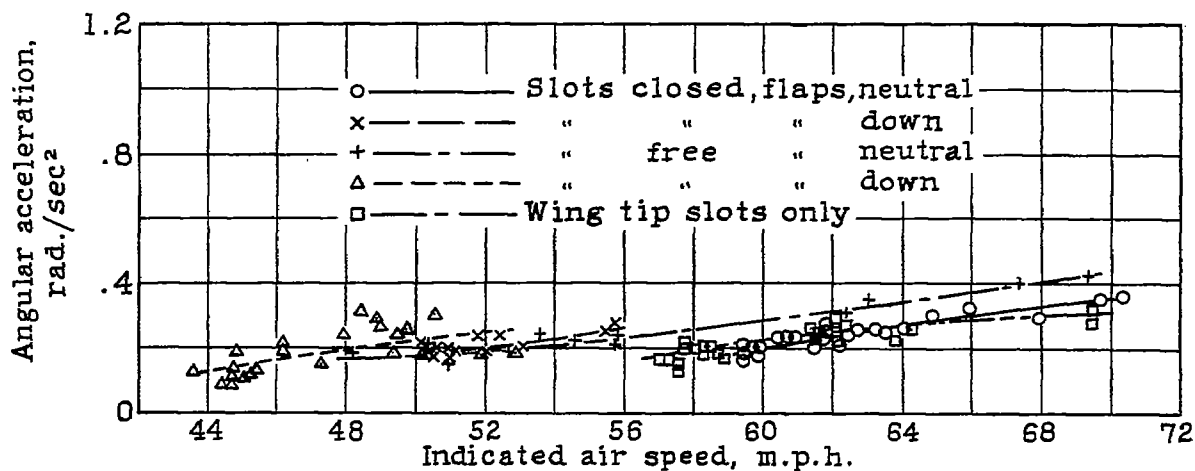
Figure 7.- Variation of maximum yawing acceleration about body
        axis, with indicated air speed, for full positive rudder
deflection. (All wing conditions.)
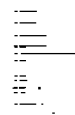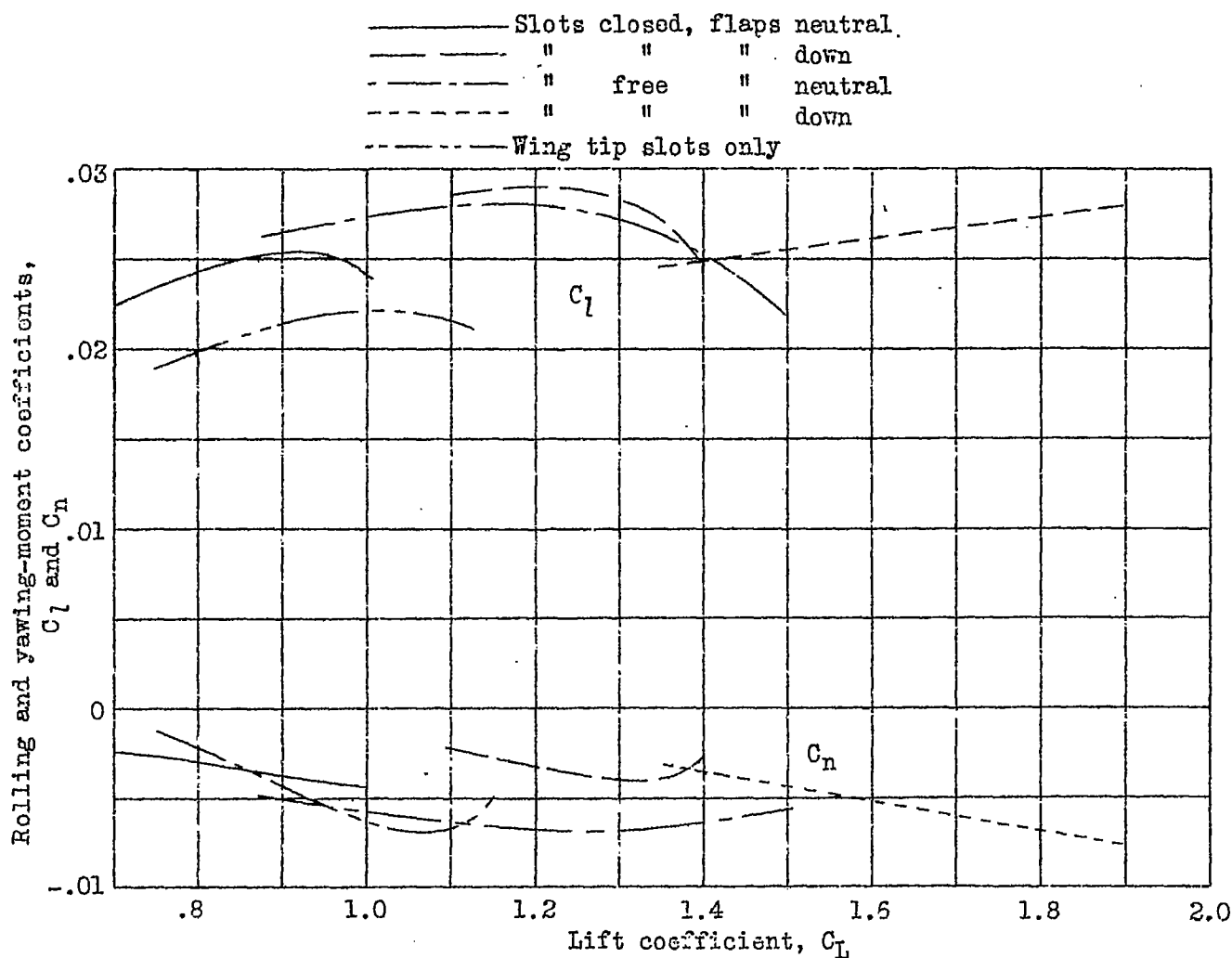
Figure 6.- Variation of coefficients of rolling and yawing moment about body axes, with lift coefficient, for full positive aileron deflection. (All wing conditions.)

Fig. 6

Slots closed, flaps neutral
"   "   "   down
"   free   "   neutral
"   "   "   down
Wing tip slots only
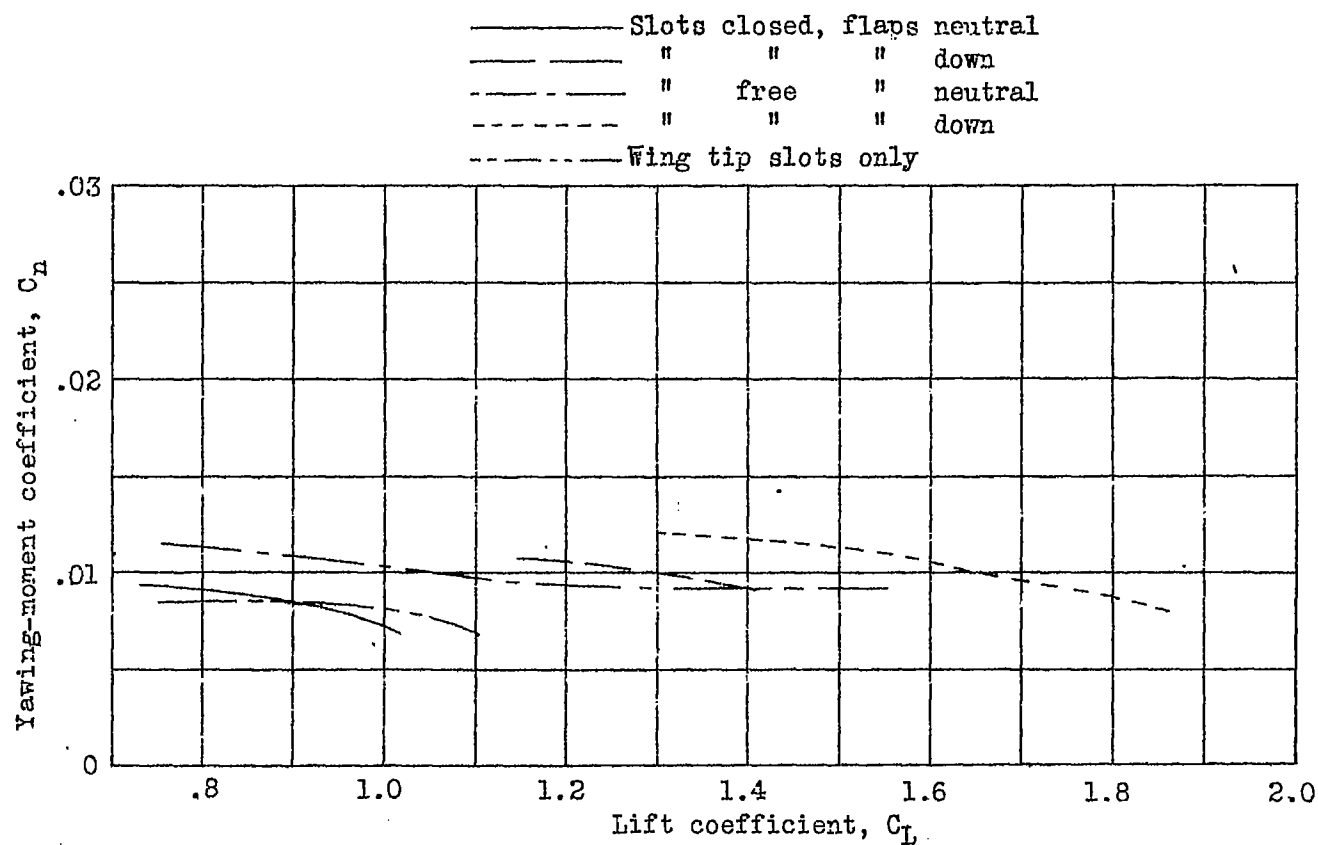
Figure 8.- Variation of yawing-moment coefficient about body axis, with lift coefficient , for full positive rudder deflection. (All wing conditions.)

Fig. 8

Figure 9.- Comparison of yawing-moment coefficients produced by full positive rudder deflection and full positive aileron deflection. (All wing conditions.)

Fig. 9
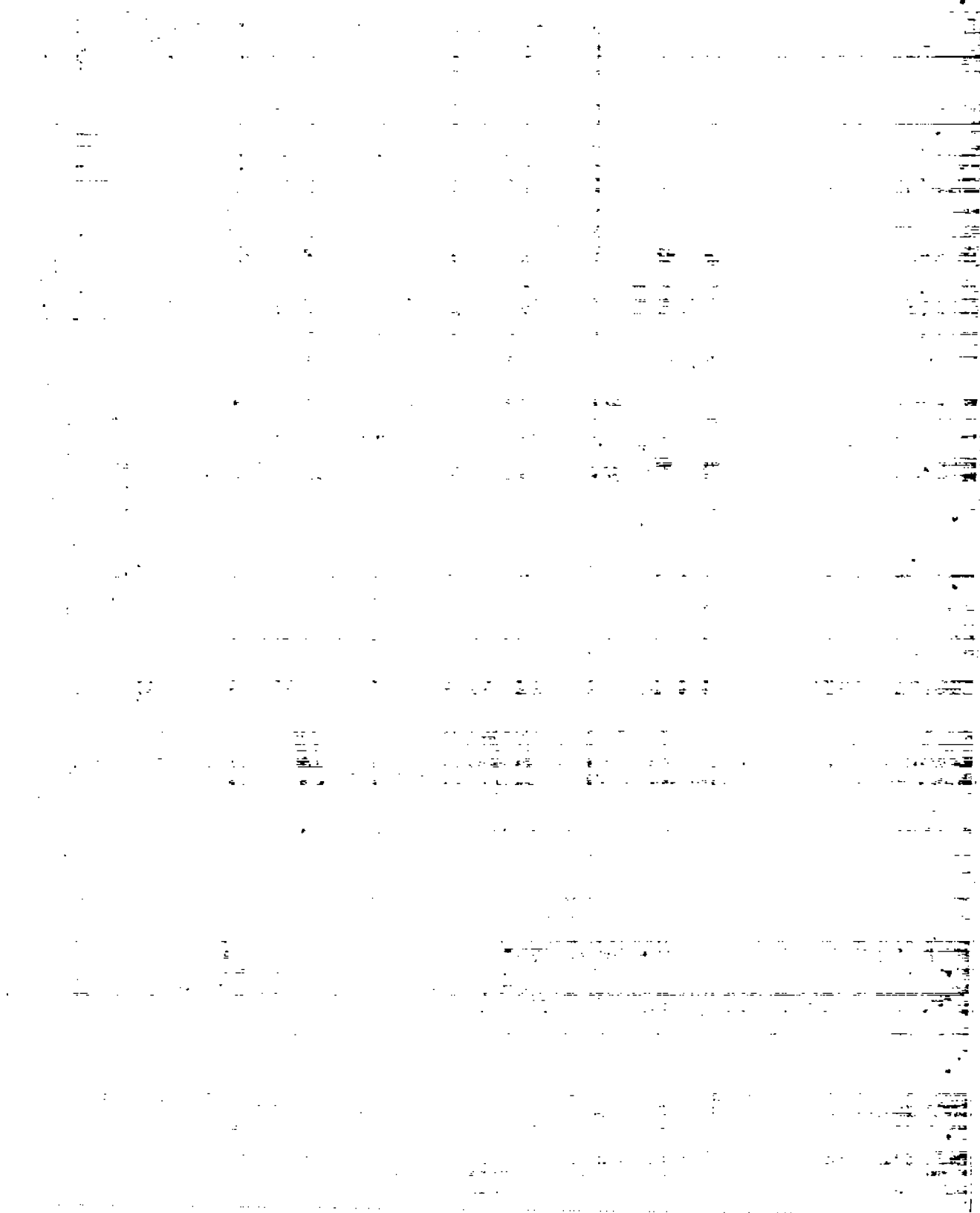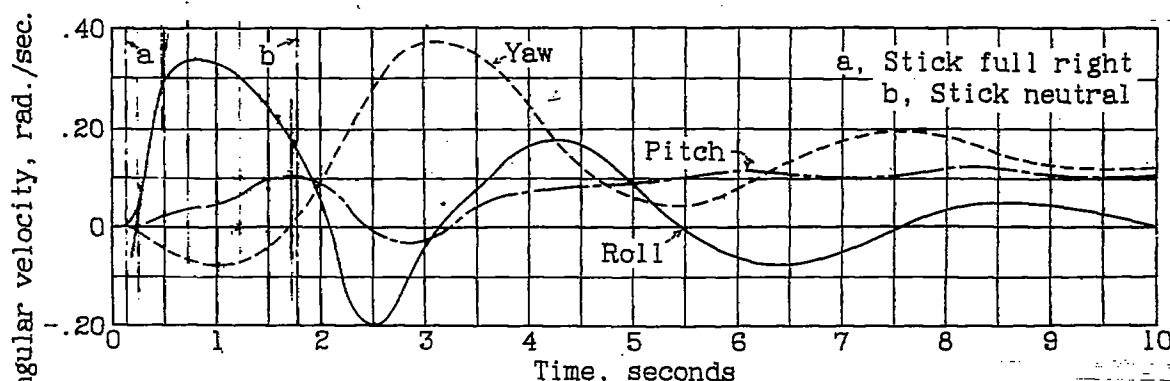
Figure 10.-Time history of angular velocities about the body axes for an initial full positive aileron deflection,followed two seconds later by return to neutral. (Slots locked closed, flaps neutral. Angle of attack of thrust line = 15°. Indicated air speed = 60.4 m.p.h.)
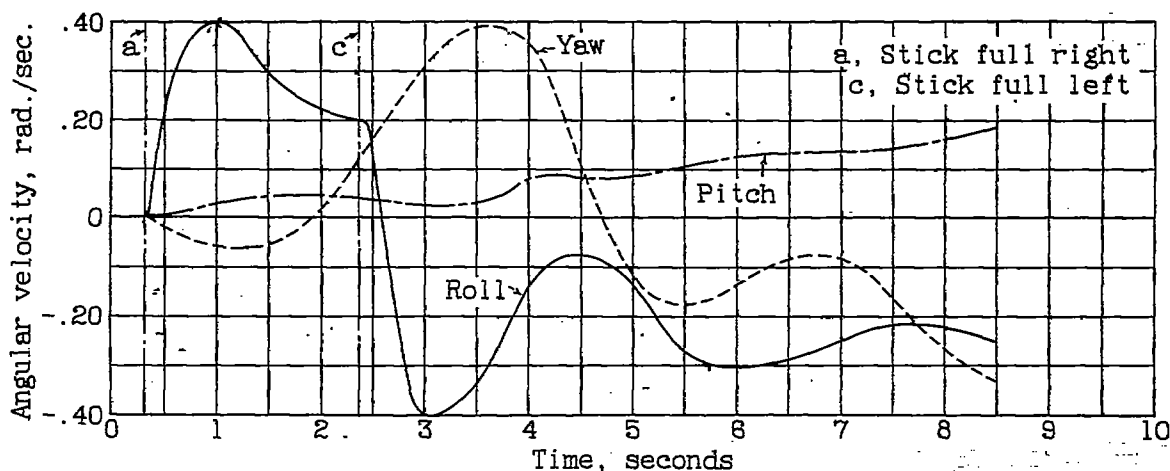
Figure 11.-Time history of angular velocities about the body axes for an initial full positive aileron deflection, followed two seconds later by full negative aileron deflection. (Slots locked closed, flaps neutral. Angle of attack of thrust line = 12.4°. Indicated air speed = 62.8 m.p.h.)
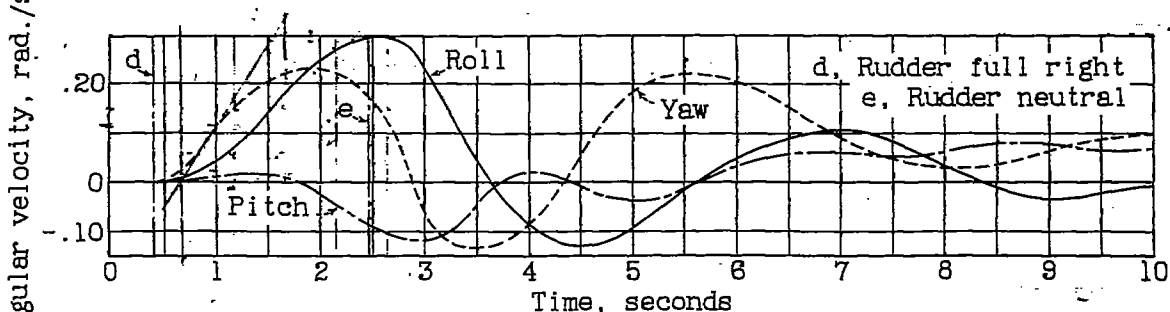
Figure 12.-Time history of angular velocities about the body axes for an initial full positive deflection of the rudder, followed two seconds later by return to neutral. (Slots locked closed, flaps neutral. Angle of attack of thrust line = 12.4°. Indicated air speed = 62.8 m.p.h.)
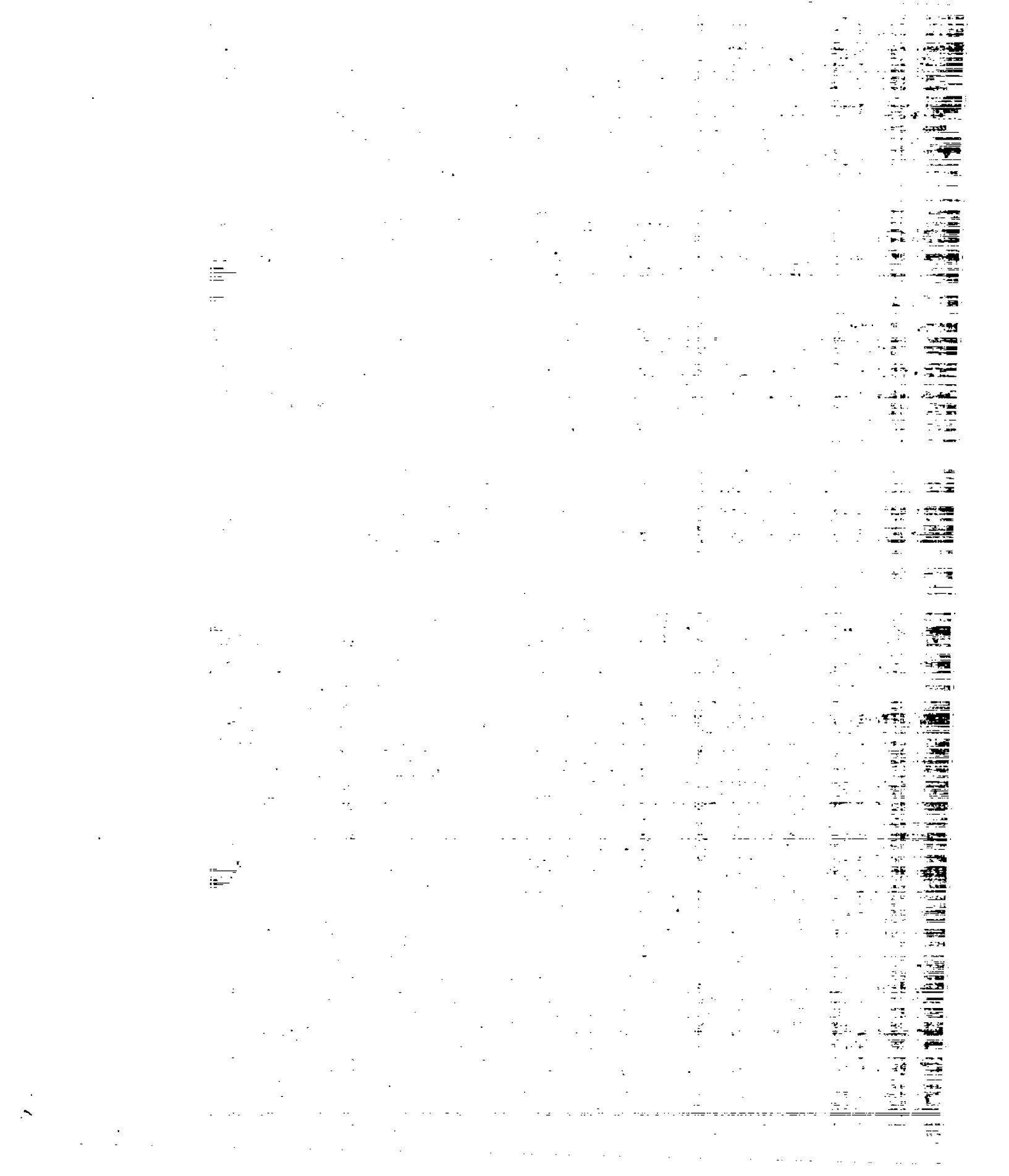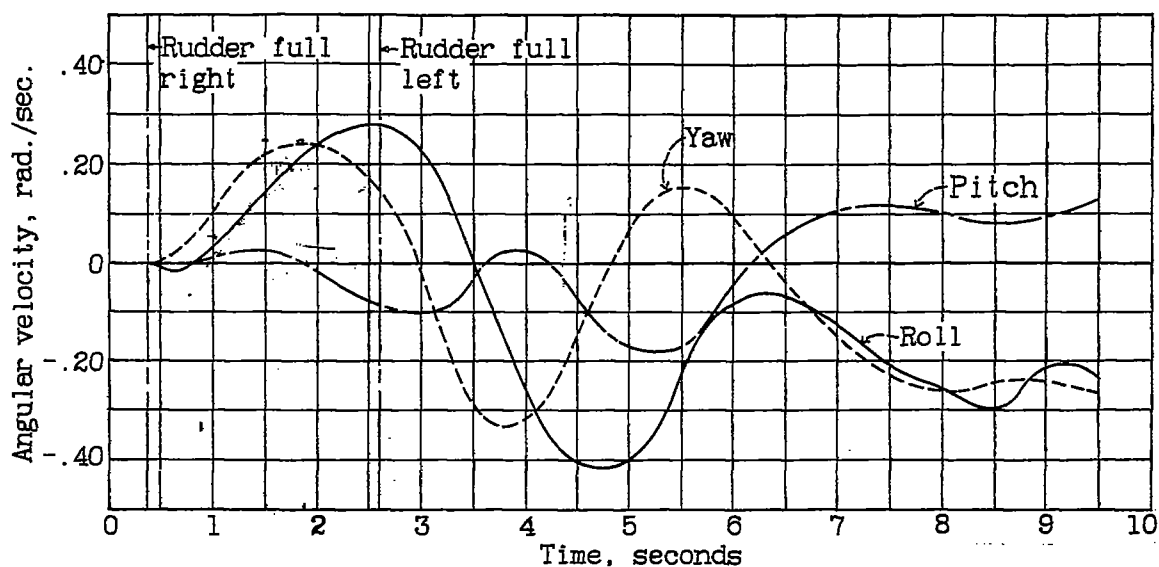
Figure 13.- Time history of angular velocities about the body axes,
        for an initial full positive rudder, followed two seconds
later by full negative rudder deflection. (Slots locked closed and
flaps neutral. Angle of attack of thrust line - 13.2°. Indicated air
speed = 61.7 m.p.h.)
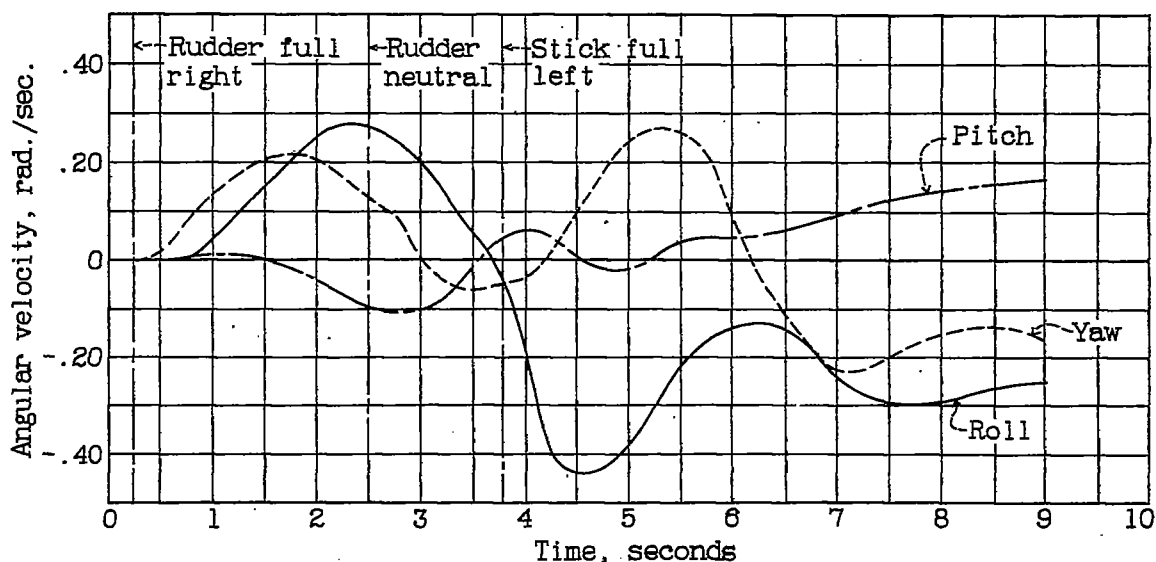
Figure 14.- Time history of angular velocities about the body axes,
        for an initial full positive deflection of the rudder,
followed two seconds later by return to neutral and full negative
deflections of the ailerons. (Slots locked closed, flaps neutral.
Angle of attack of thrust line = 14.1°. Indicated air speed = 61.1
m.p.h.)
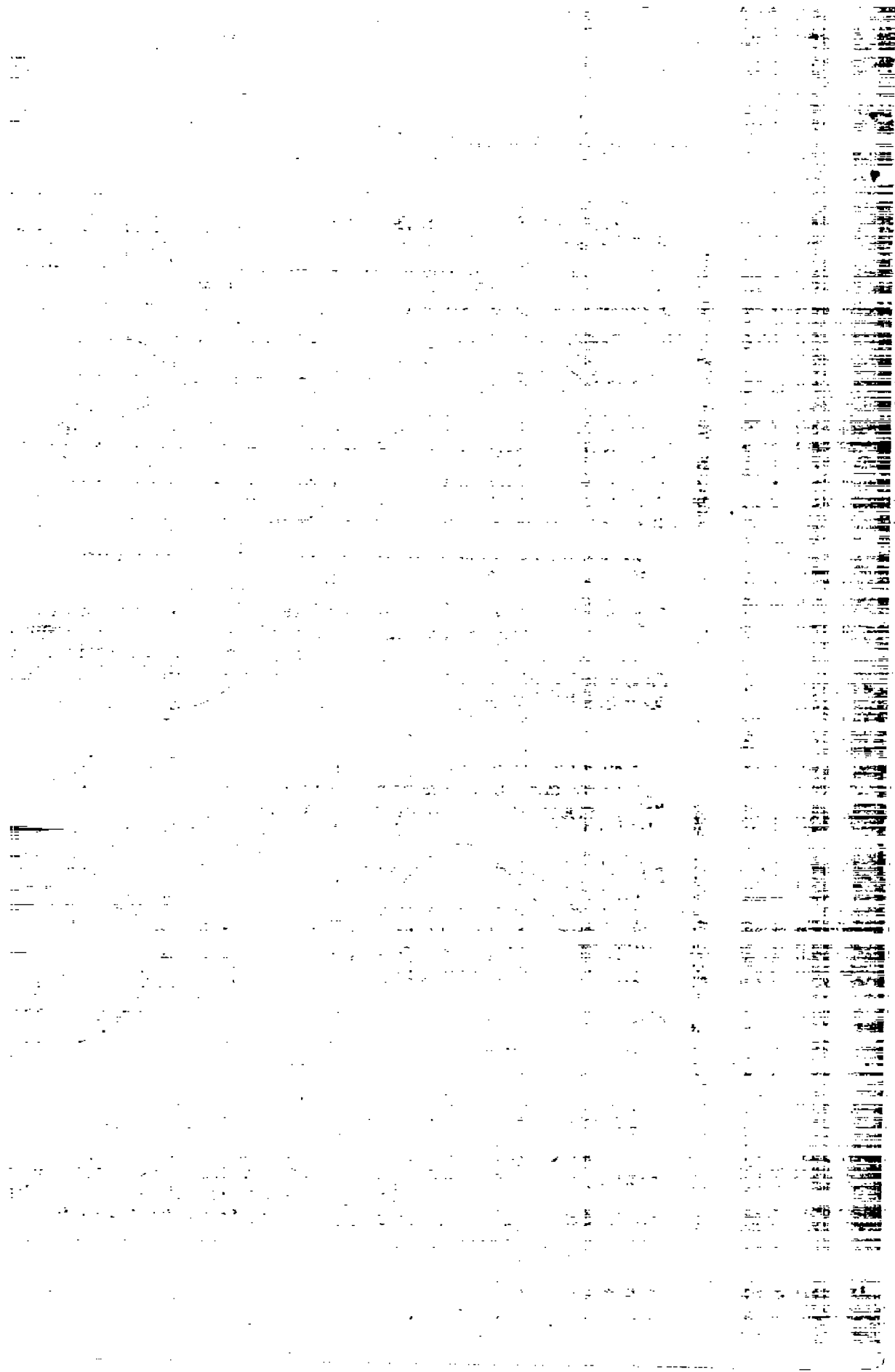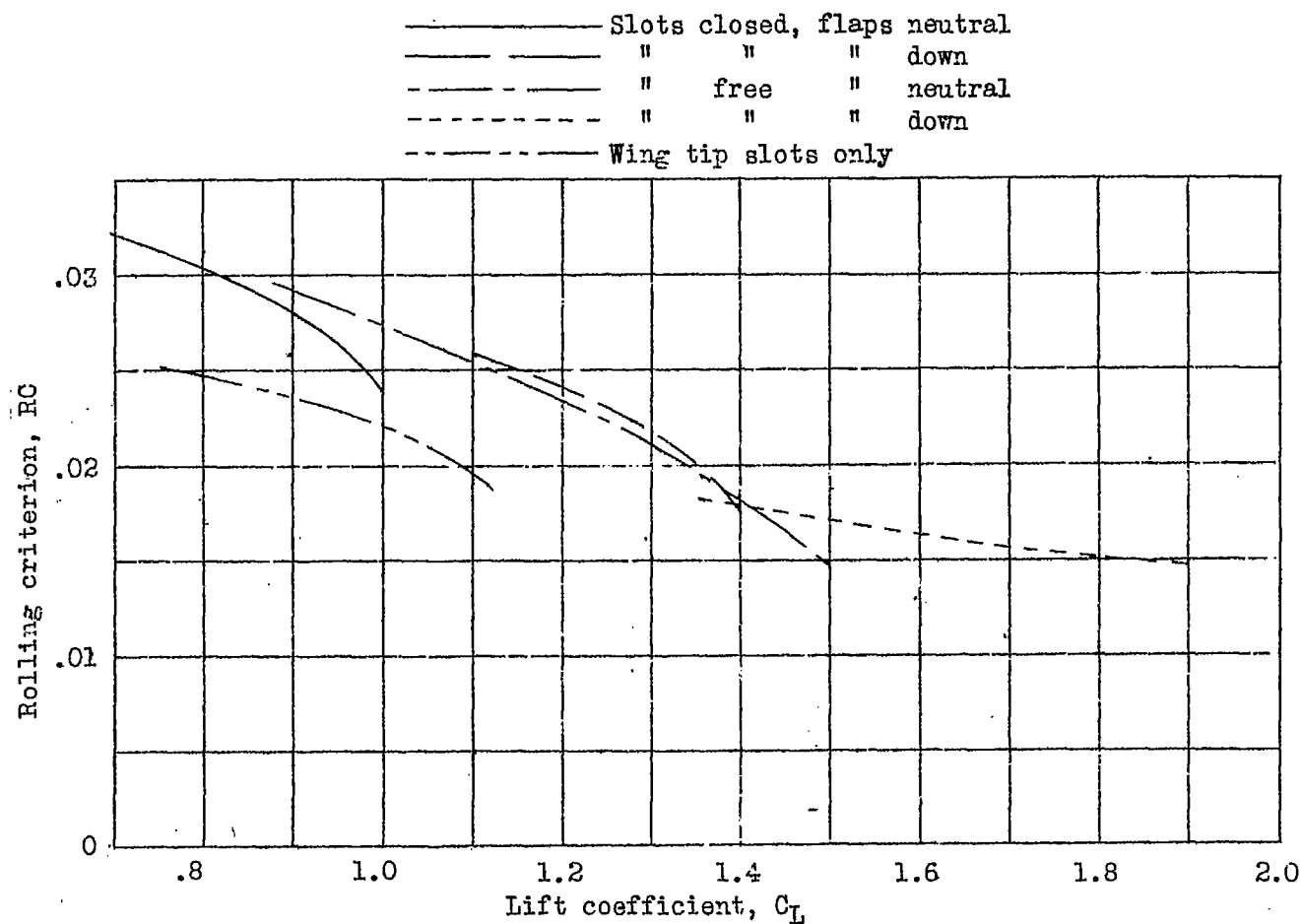
Figure 15.- Variation of rolling criterion, referred to body axis, with lift coefficient, for full positive aileron deflection. (All wing conditions.)

Fig. 15

a,   Right aileron angle
b,   Angular velocity of roll
c,   Point of maximum angular acceleration
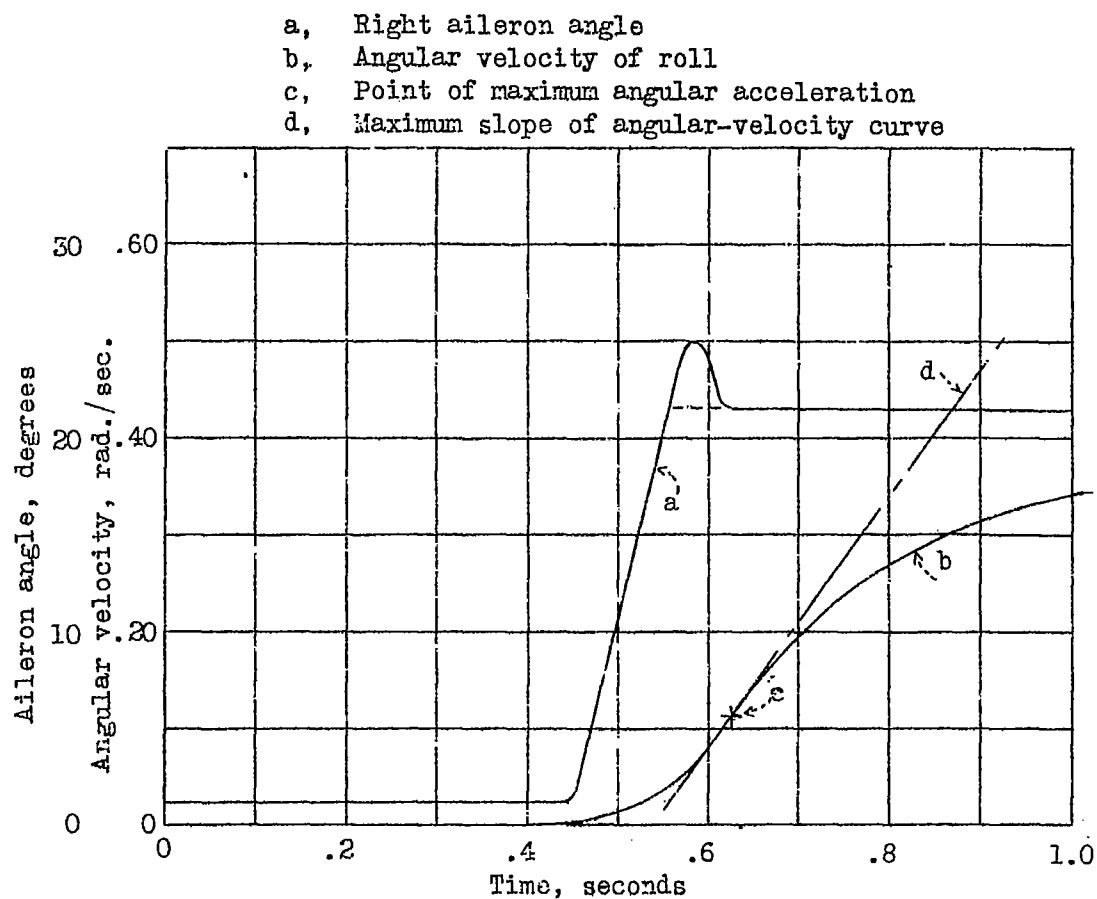d,   Maximum slope of angular-velocity curve

Figure 16.- Time history of positive aileron movement and resulting
        rolling velocity.

Fig. 16